Status of Higgs CP Studies

Andrei Gritsan
Johns Hopkins University

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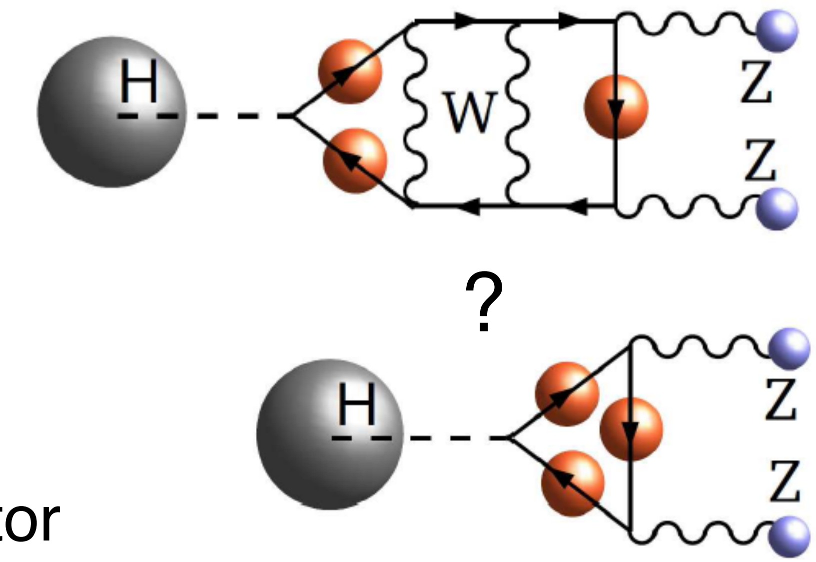
Snowmass Energy Frontier Workshop, EF01/02 Session

CP-violating H(125) Couplings



- CP-violating H(125) couplings
  - — tiny in the SM, excellent null-test
  - — well-defined stand-alone reference measurement
  - — potential baryogengesis connected to the Higgs sector
  - — input to the global EFT fits, which currently focus on CP-even Operators
  - — $pp,\ e^+e^-,\ \gamma\gamma,\ \mu^+\mu^-\ (\sqrt{s})$ have their unique features in CP of H(125)
  - — complementarity to the EDM measurements and Flavor Physics

- Identify key reference measurements to compare facilities
  - — focus on direct H production (including off-shell)
  - — connect to indirect (virtual, low-energy) probes

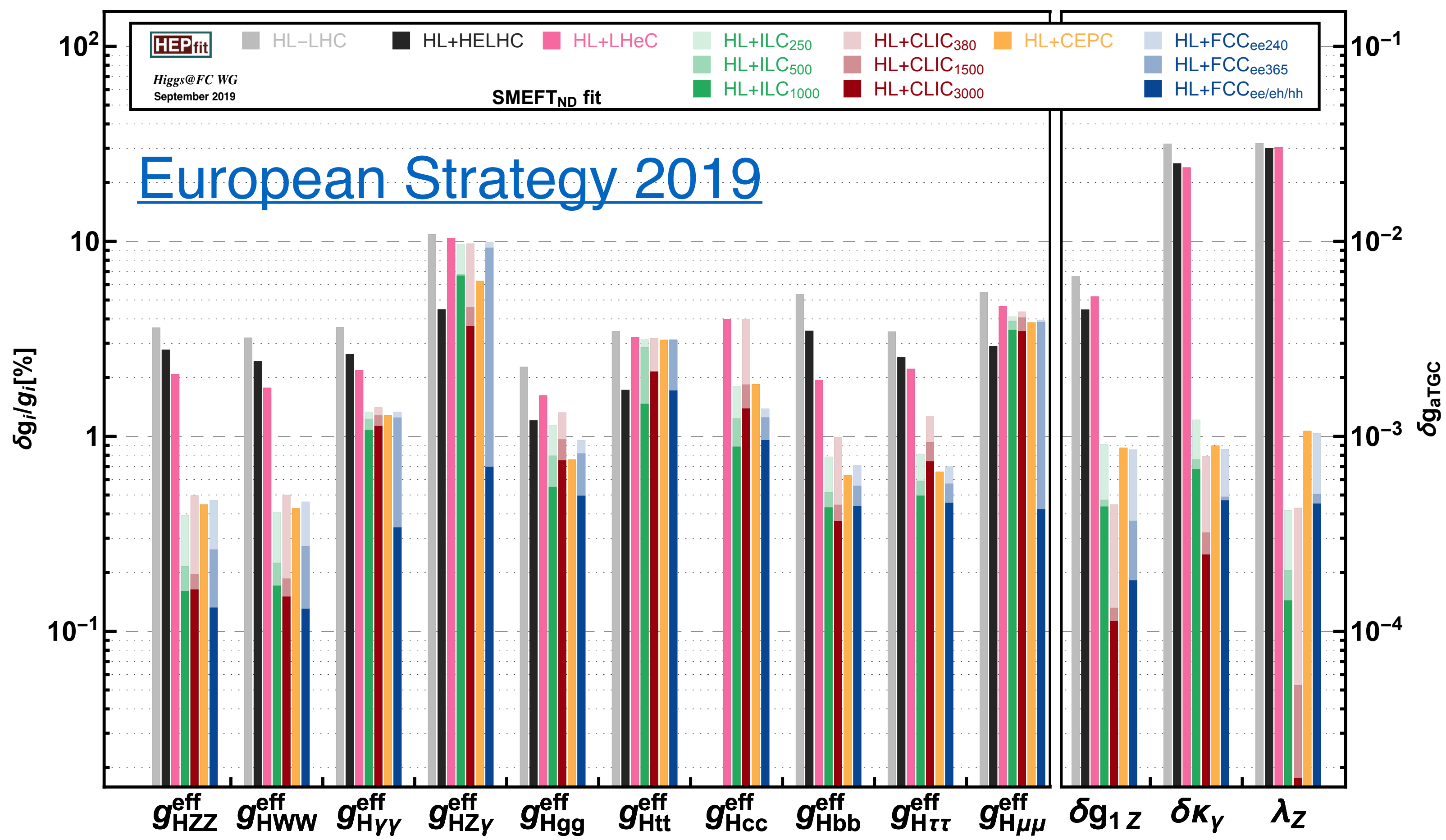
EFT Approach to CP

- Tradeoff between complexity/reach and simplicity/scope

  — what is better to illustrate certain point: implications for colliders?

e.g. effective couplings were chosen for European Strategy (CP-even):

$$g_{HX}^{\mathrm{eff}\;2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}$$



- look for structure

  if we include CPV:

$$f_{\mathrm{CP}}^{HX} \equiv \frac{\Gamma_{H\to X}^{\mathrm{CP\,odd}}}{\Gamma_{H\to X}^{\mathrm{CP\,odd}} + \Gamma_{H\to X}^{\mathrm{CP\,even}}}$$

(Snowmass-2013)

$$\mathrm{SMEFT_{ND}} \equiv \{\delta m,\, c_{gg},\, \delta c_z,\, c_{\gamma\gamma},\, c_{z\gamma},\, c_{zz},\, c_{z\Box},\, \delta y_t,\, \delta y_c,\, \delta y_b,\, \delta y_\tau,\, \delta y_\mu,\, \lambda_z\}$$
$$+\left\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_\ell, (\delta g_L^{Ze})_\ell, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_\ell\right\}_{q_1=q_2\neq q_3,\ \ell=e,\mu,\tau}$$

Higgs CP from Snowmass-2013

- Higgs Working Group Report of the Snowmass-2013 Community Planning Study

  Chapter 1.4 devoted to spin and CP: arXiv:1310.8361

  – pp, e^+e^-, $\gamma\gamma$, $\mu^+\mu^-$ $(\sqrt{s})$ have their unique features in CP of H(125)

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4\cdot10^{-4}$	$1.2\cdot10^{-4}$	$7\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7\cdot10^{-4}$	$1.3\cdot10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

spin=0 established by now

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\text{CP odd}}}{\Gamma_{H\to X}^{\text{CP odd}} + \Gamma_{H\to X}^{\text{CP even}}}$$

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ggH	0.50	0.16	–	–	–	–	–	–	$<10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$<10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$<10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$<10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$<10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$<10^{-2}$

comparison across facilities

targeted couplings

theoretical interest

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

parameters of interest

$$f_{CP}^{HX} \equiv \frac{\Gamma^{\rm CP\,odd}_{H\to X}}{\Gamma^{\rm CP\,odd}_{H\to X} + \Gamma^{\rm CP\,even}_{H\to X}}$$

Target for Snowmass-2022

- Revisit Snowmass-2013 studies

  — new realist LHC studies appeared

  e.g. CP in $Htt, H\tau\tau, Hgg$

  — recent update from Higgs Physics at the HL-LHC and HE-LHC

  — new phenomenological studies performed

  — Effective Field Theory approach gained popularity

  — any new ideas, techniques, studies to be incorporated

- Plan to collect input in a Higgs CP writeup:

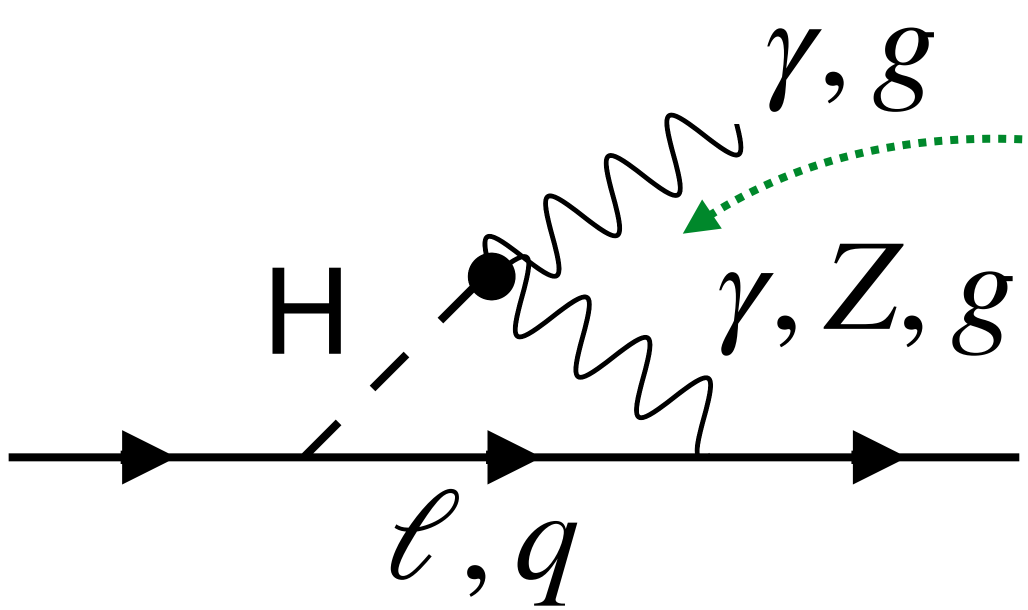
  — Gitlab area created: https://gitlab.cern.ch/snowmass21-ef01/higgs-cp

“Table-Top,” “Lower-Energy,” Direct H production

- Electric Dipole Moment (EDM) of electron $d_e < 1.1 \times 10^{-29}\ e\,\mathrm{cm}$

$d_e^{\mathrm{SM}} \sim 10^{-38}\ e\,\mathrm{cm}$

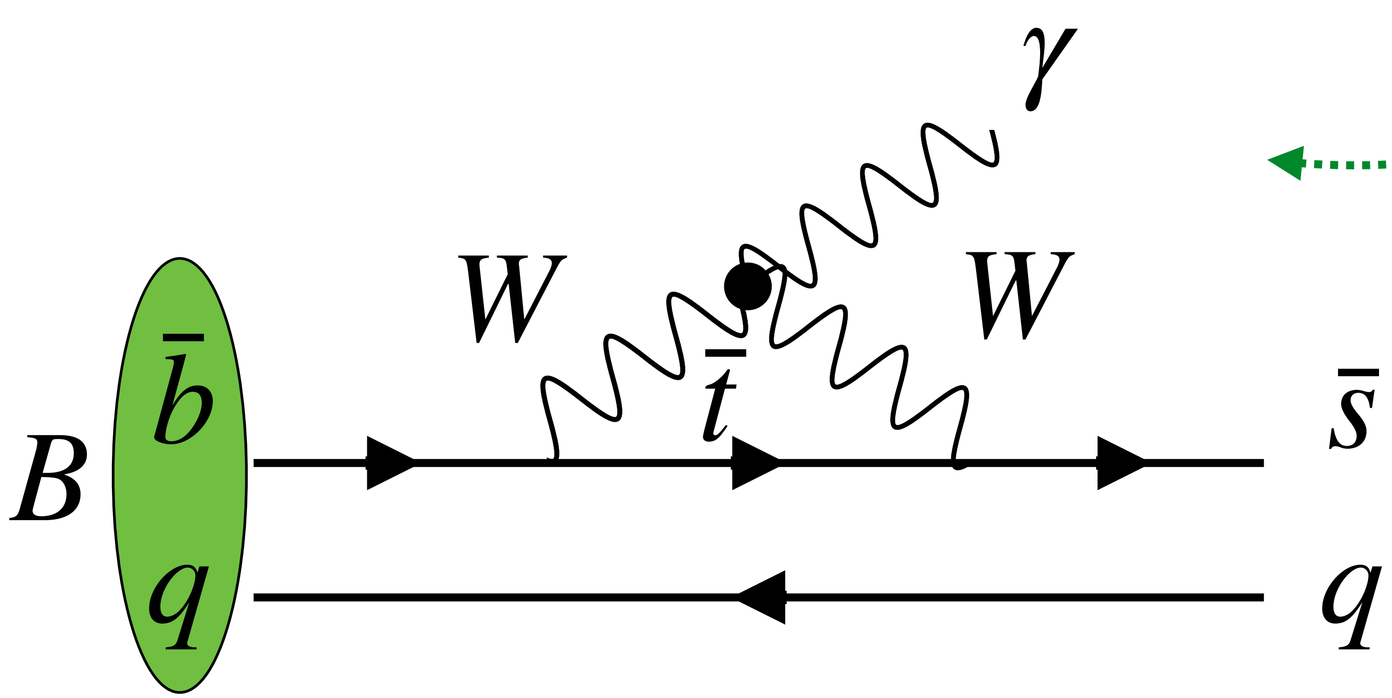
$d_n < 3.0 \times 10^{-26}\ e\,\mathrm{cm}$



complementary in EFT

SU(2)xU(1)

- Heavy-Quark meson decays:



Theoretical Models and connection to EDM/B/EW

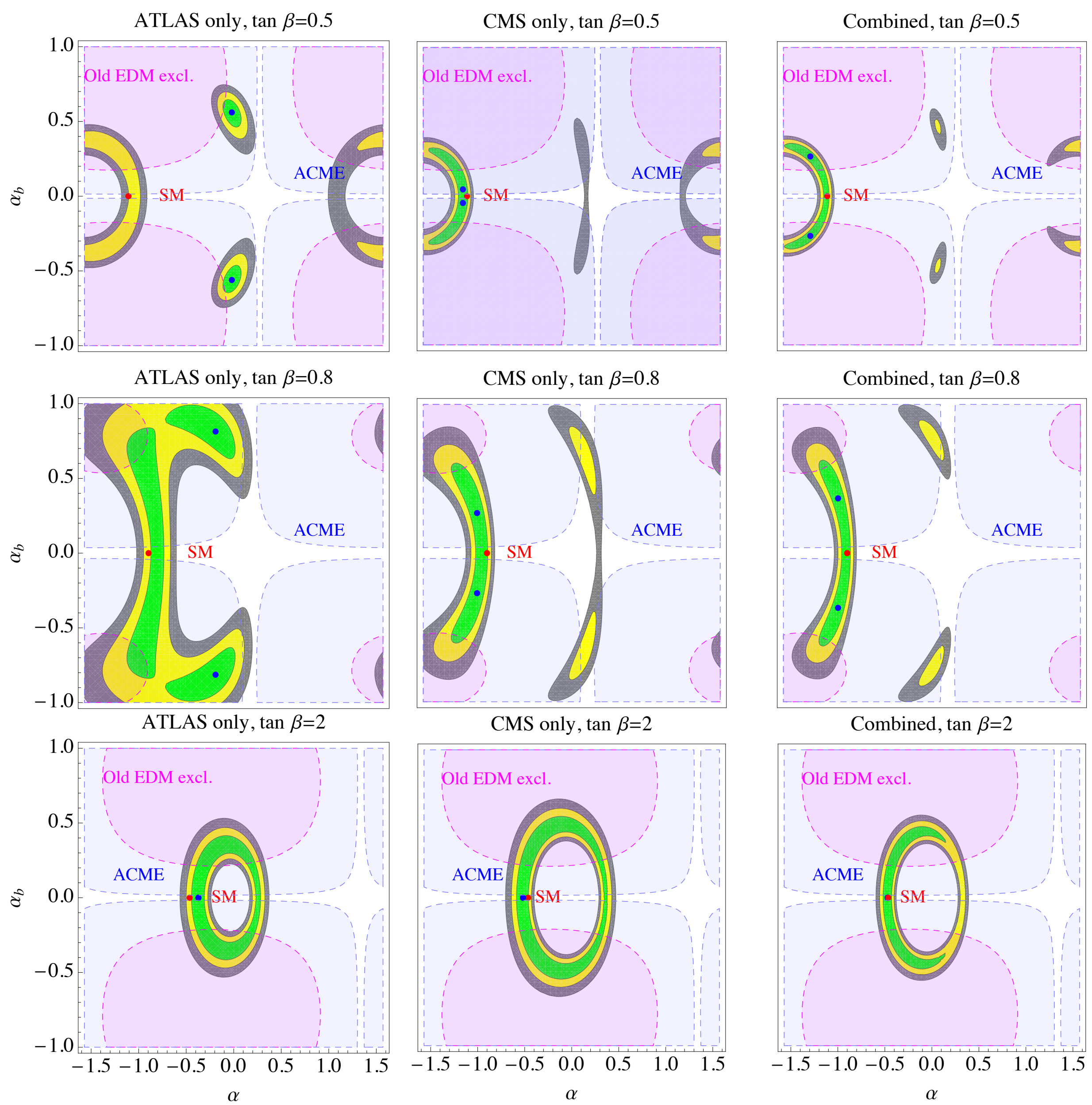
- Representative model analysis

  Hff in 2HDM: [arXiv:1304.0773](https://arxiv.org/abs/1304.0773)

  — motivated $f_{CP} < 0.01$ $(\alpha_b < 0.1)$

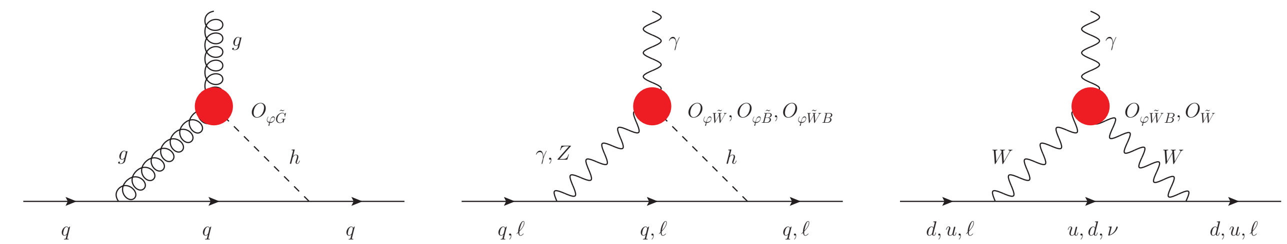
  — to be updated to more recent results

allowed range for CP-odd α_b

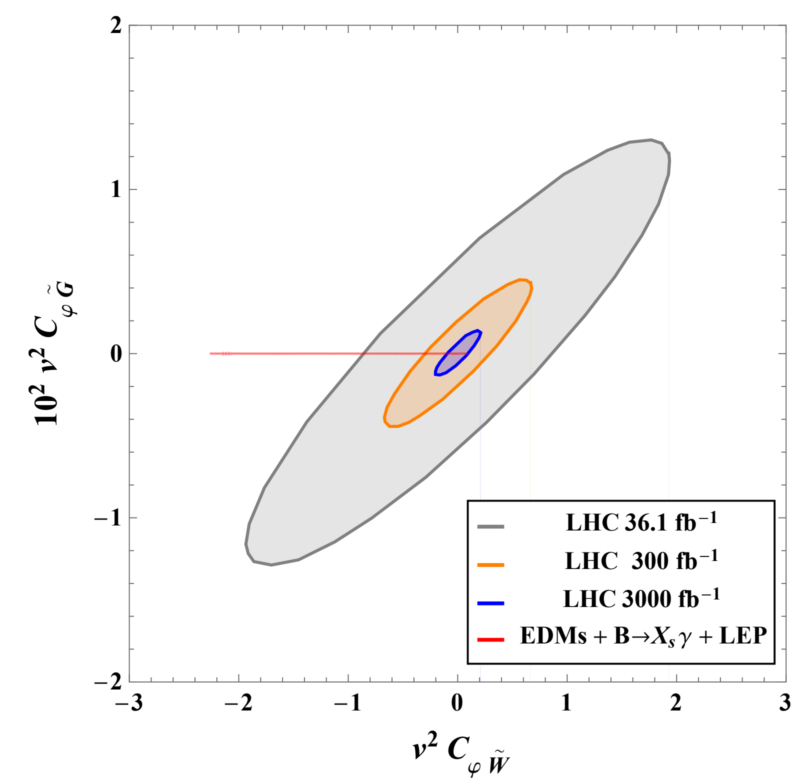


- EFT analysis of EDM and LHC:

  From tabletop to the LHC: [arXiv:1903.03625](https://arxiv.org/abs/1903.03625)



	Low energy	LHC (3000 fb^{-1})
$v^2\, C_{\varphi\tilde{B}}$	$[-0.4, 0.00]$	$[-0.3, 0.3]$
$v^2\, C_{\varphi\tilde{W}}$	$[-2.3, 0.02]$	$[-0.17, 0.17]$
$v^2\, C_{\varphi\tilde{W}B}$	$[-1.3, 0.01]$	$[-0.39, 0.39]$
$v^2\, C_{\varphi\tilde{G}}$	$[-1.3, 1.3]\cdot 10^{-5}$	$[-9.0, 9.0]\cdot 10^{-4}$



Unique features of Facilities: $\gamma\gamma$ production

- Photon collider is unique with focus on $H\gamma\gamma$ coupling
  - photon beam polarization is critical for CP
  - most interesting parameter:

$$\mathcal{A}_3 = \frac{|A_{\parallel}|^2 - |A_{\perp}|^2}{|A_{\parallel}|^2 + |A_{\perp}|^2} = \frac{2\mathcal{R}e\,(A^*_{--}A_{++})}{|A_{++}|^2 + |A_{--}|^2} = \frac{|a_2|^2 - |a_3|^2}{|a_2|^2 + |a_3|^2} = (1 - 2f_{CP})$$

Detecting and Studying Higgs Bosons at a Photon-Photon Collider: arXiv:hep-ph/0110320

  - measure as asymmetry between $\parallel$ and $\perp$ linear polarizations

for $E_0 = 110$ GeV and $\lambda = 1\,\mu$m: $f_{CP} = \sin^2(\alpha^{\gamma\gamma}) \sim \pm\, 0.06$

at $2.5 \cdot 10^{34} \times 10^7 = 250\,\text{fb}^{-1}$

- Interesting to revisit and compare to pp and e^+e^-
  - need fair comparison: information from polarization, not cross section

Unique features of Facilities: $\mu^+\mu^-$ production

- Muon collider is unique with focus on $H\mu\mu$ coupling

  — muon beam transverse polarization is critical for CP

  — not many fermion couplings can be tested with polarization and CP

  later we will discuss $H\tau\tau$ and Htt (both 3rd family)

  — same transverse polarization ⇒ CP-even

  — opposite polarization ⇒ CP-odd

How Valuable is Polarization at a Muon Collider? A Test Case: Determining the CP Nature of a Higgs Boson:
arXiv:hep-ph/0003091

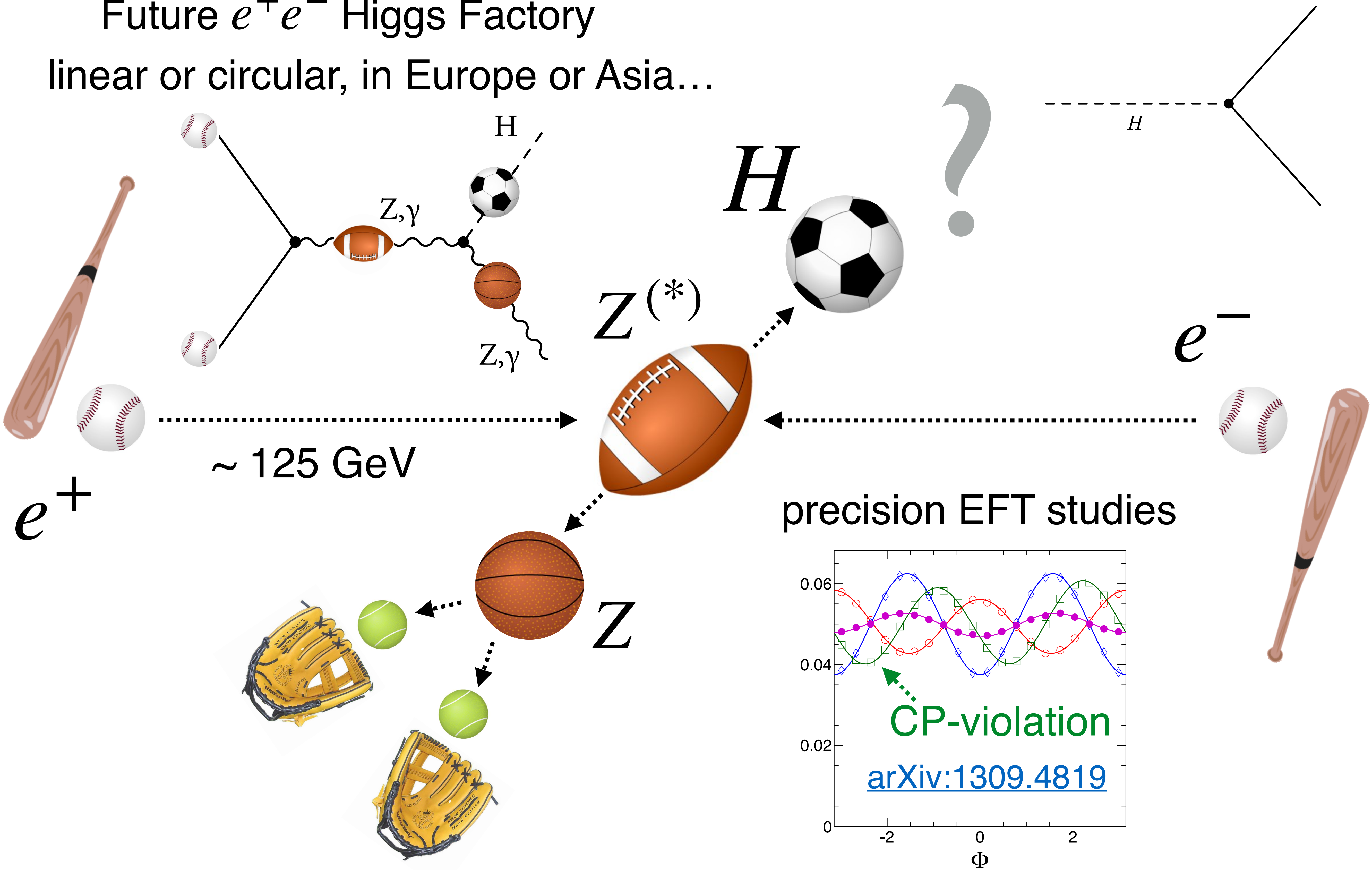
- Unique feature of the muon collider

  — though comes with a price of lumi, likely not a priority at first stage

Unique features of Facilities: e^+e^- production

Future e^+e^- Higgs Factory

linear or circular, in Europe or Asia…



Unique features of Facilities: e^+e^- production

- e^+e^- collider $\to Z^* \to ZH \;\Rightarrow\; HZZ, HZ\gamma, H\gamma\gamma$ couplings

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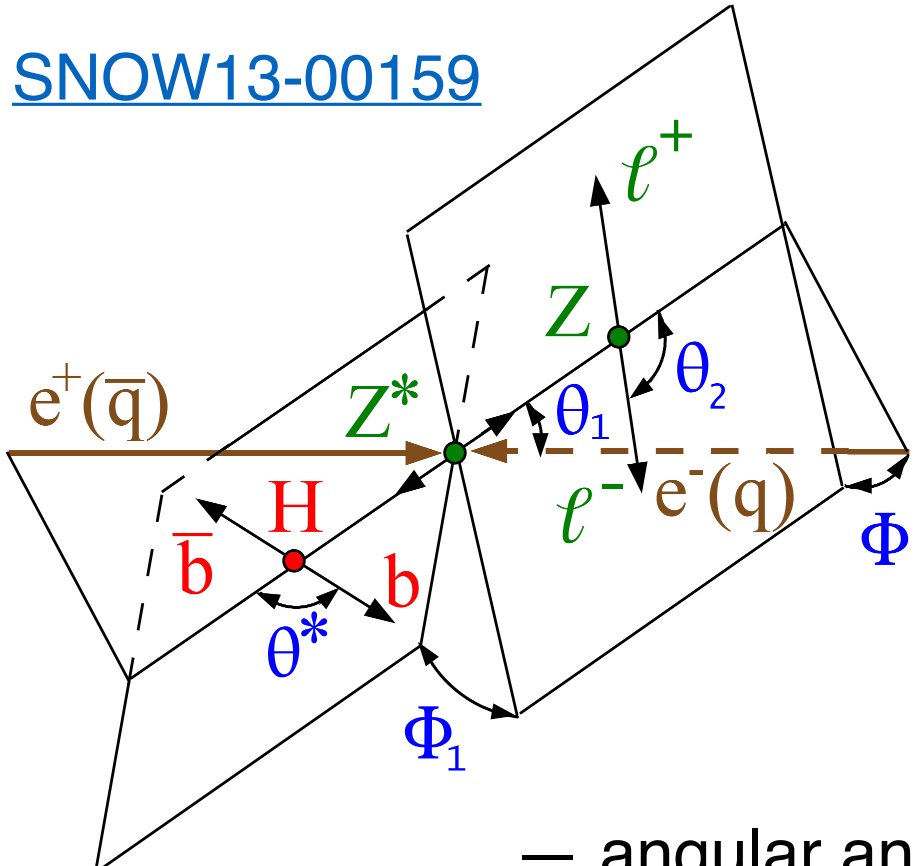
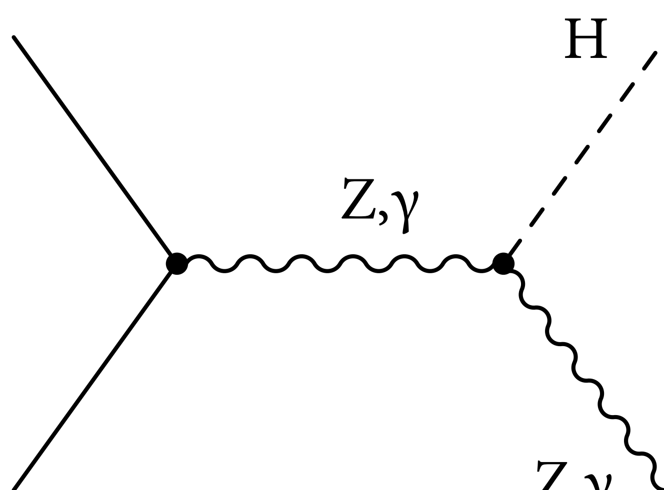
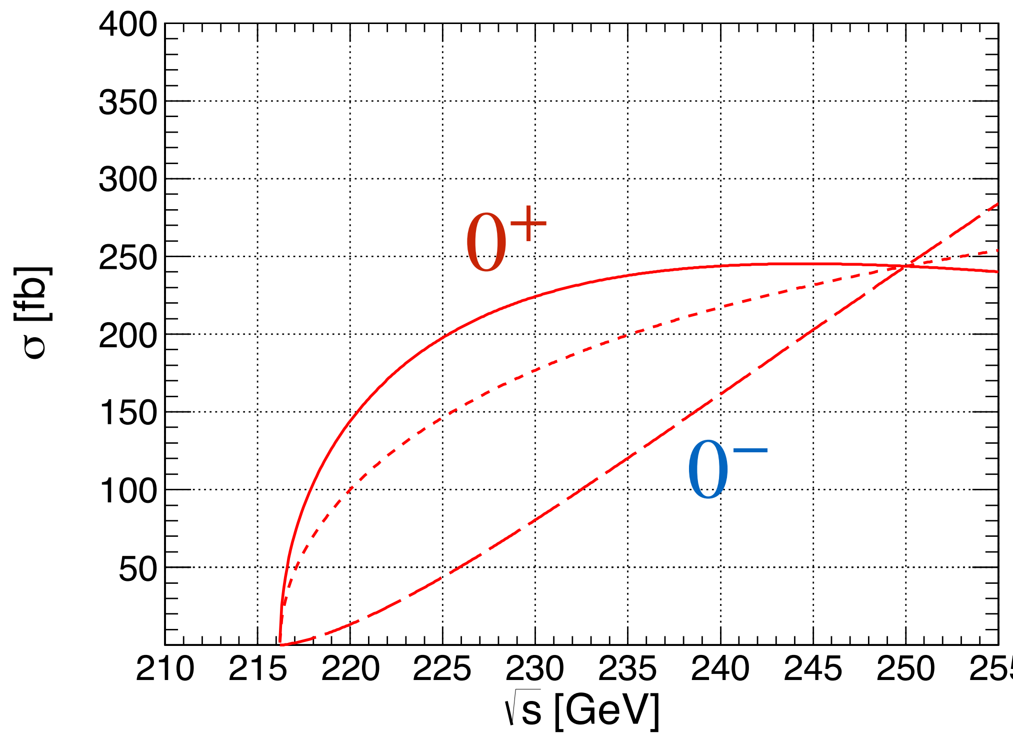
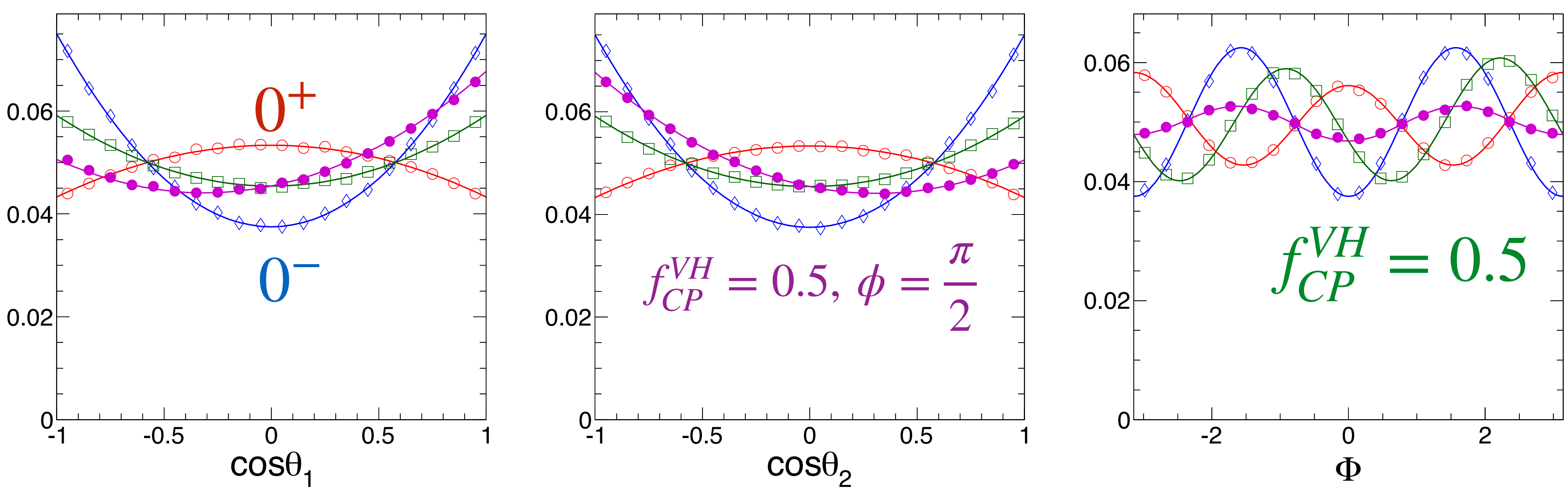




— threshold scan = q^2 dependence

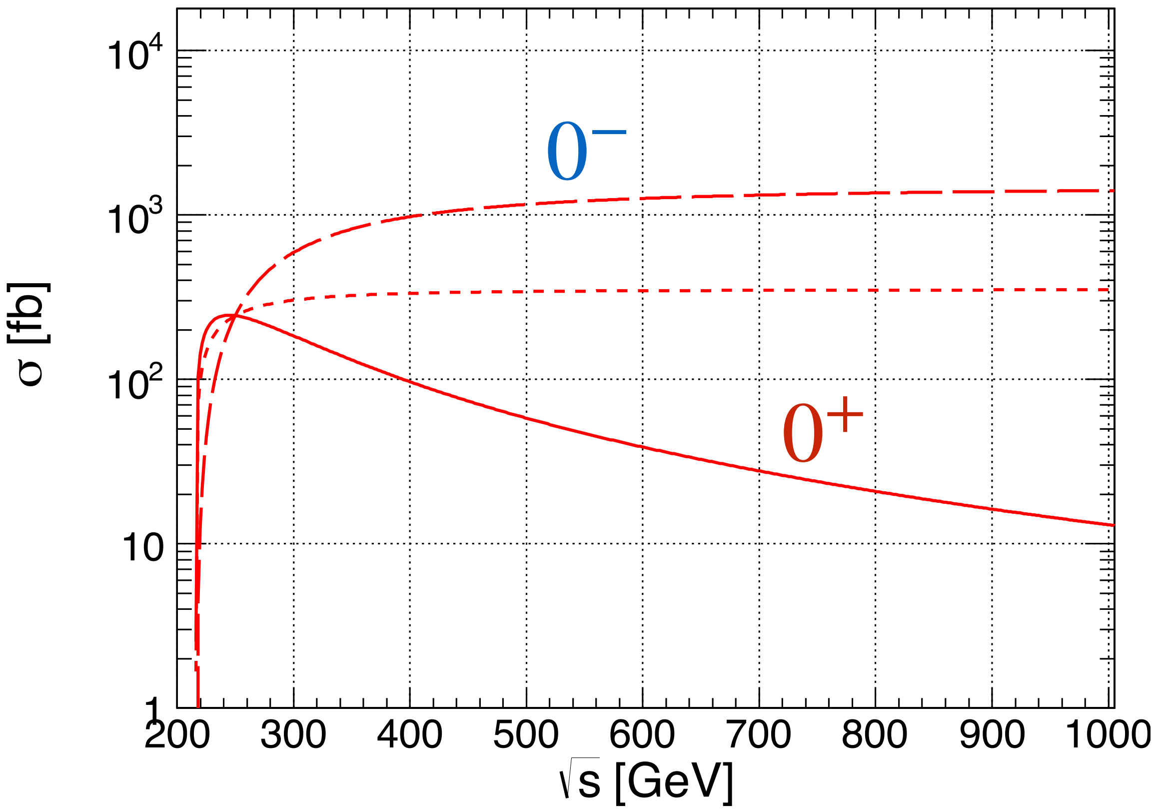


— angular analysis = polarization



e^+e^- production at higher energies (LC)

- e^+e^- collider $\to Z^* \to ZH$
- Scan q^2 dependence of HVV couplings
  $\Rightarrow$ increased sensitivity (without cutoff)



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- Linear collider $e^+e^- \to t\bar{t}H$

cross section dependence studied of 0^+ *vs.* 0^-

need dedicated CP-sensitive study (see LHC studies)

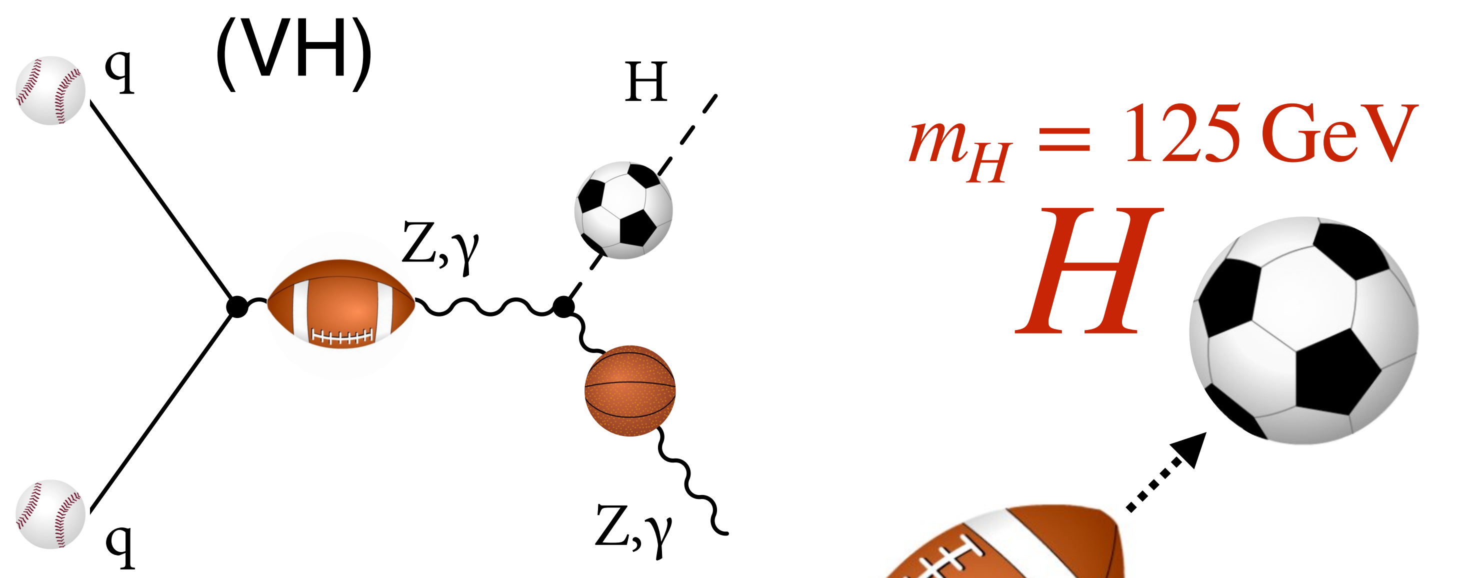
- VBF $e^+e^- \to \nu\bar{\nu}H$

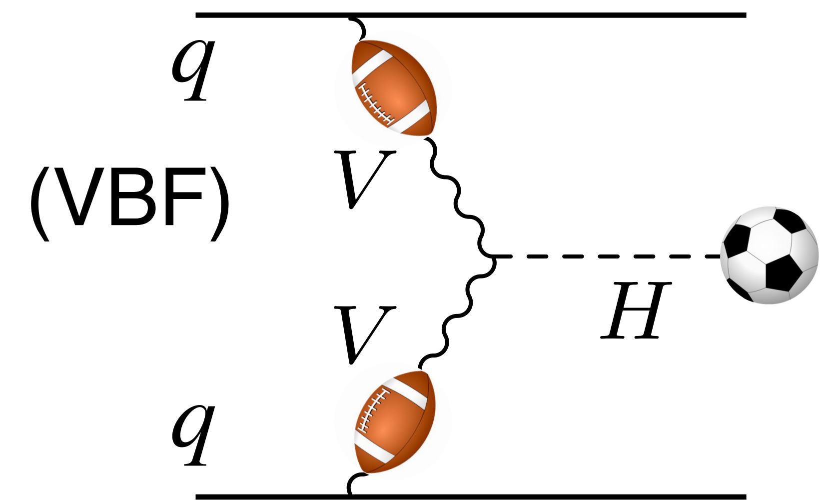
not much angular information

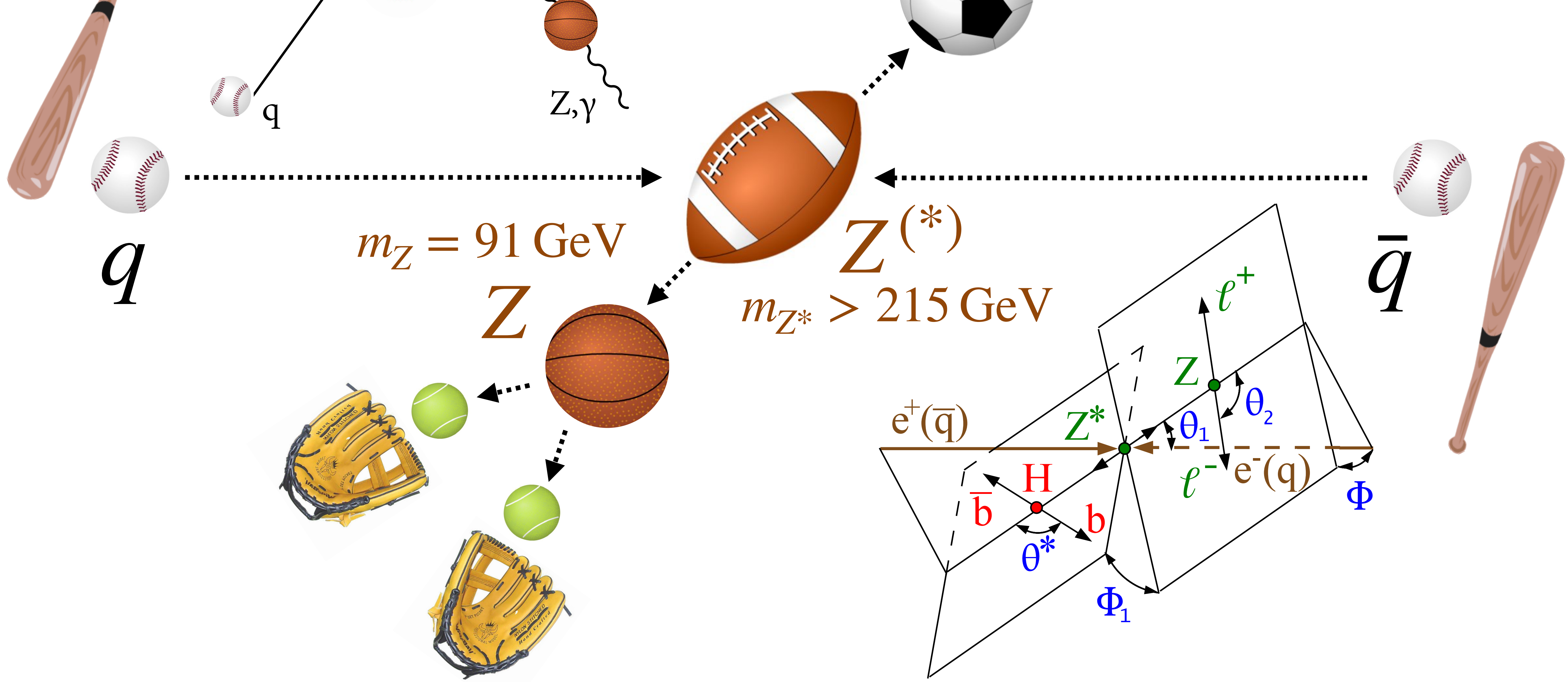
q^2-dependence through p_T^H …

Unique features of Facilities: *pp* production

- HL/HE-LHC or Future *pp* Collider



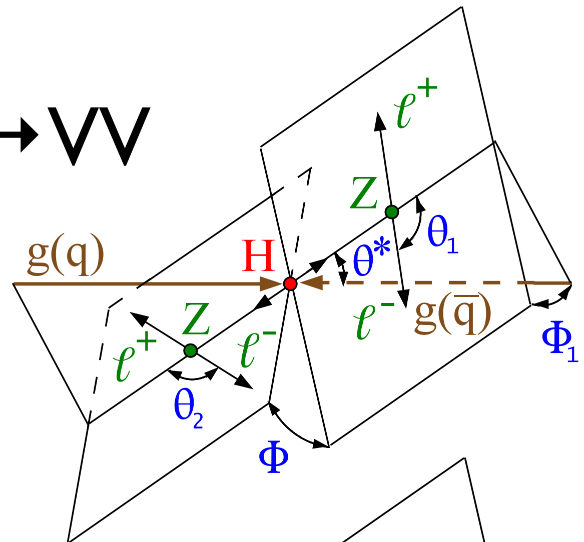




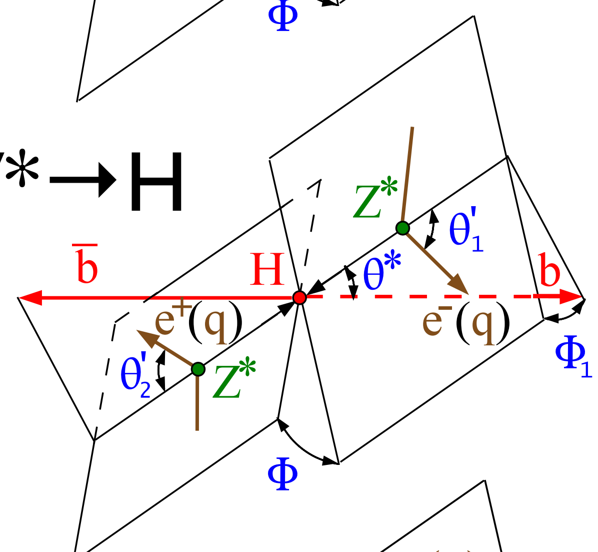
Unique features of Facilities: pp production

- $pp \to V^* \to VH \;\Rightarrow\; HWW, HZZ, HZ\gamma, H\gamma\gamma, Hgg$ couplings

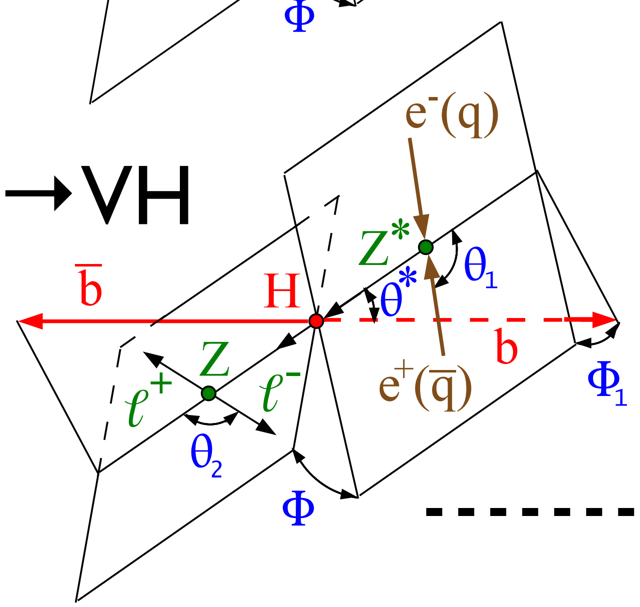
H→VV



V*V*→H



V*→VH



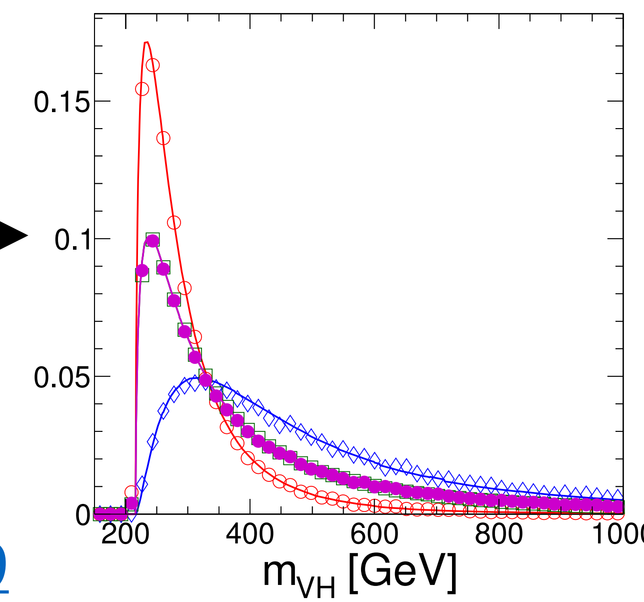
also VBF $V^*V^* \to H$ and decay $H \to VV$

pp unique $gg \to H$

benefit from LHC experience

— scan of q^2-dependence

— polarization measurement



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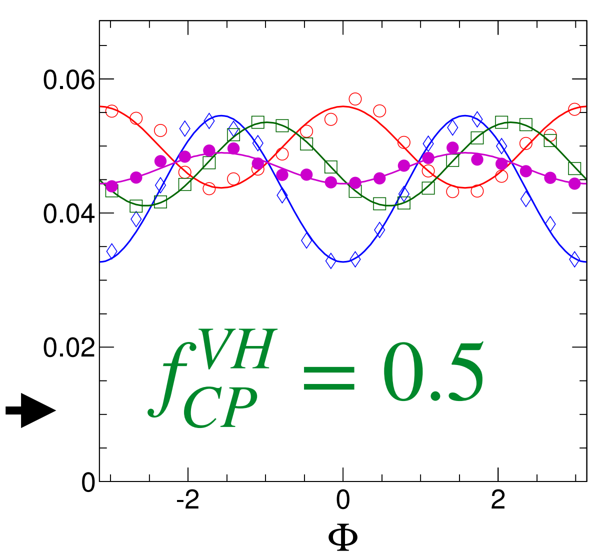
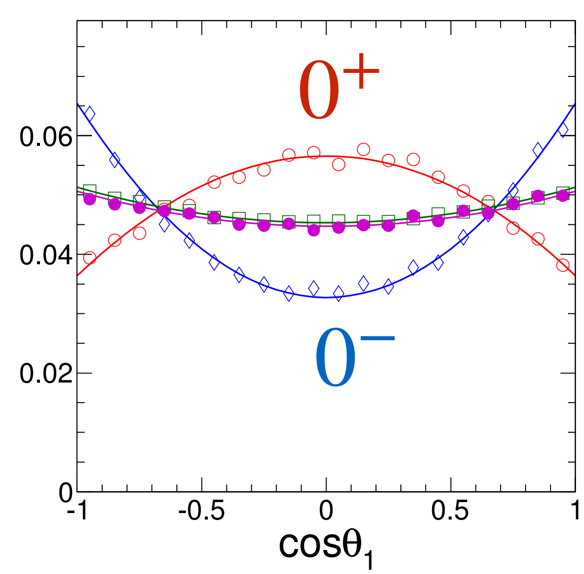
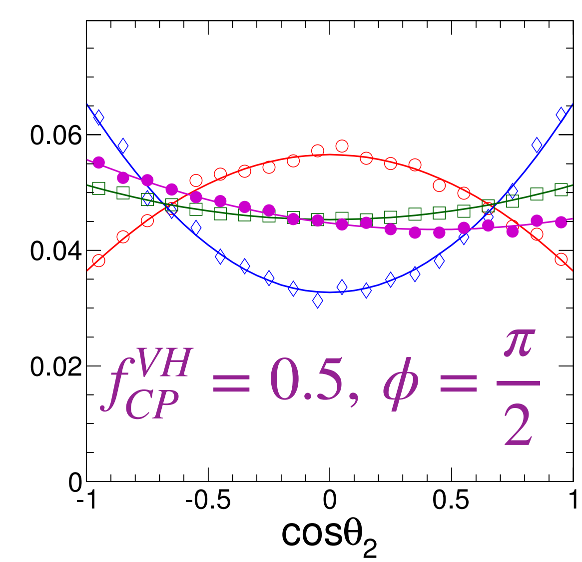




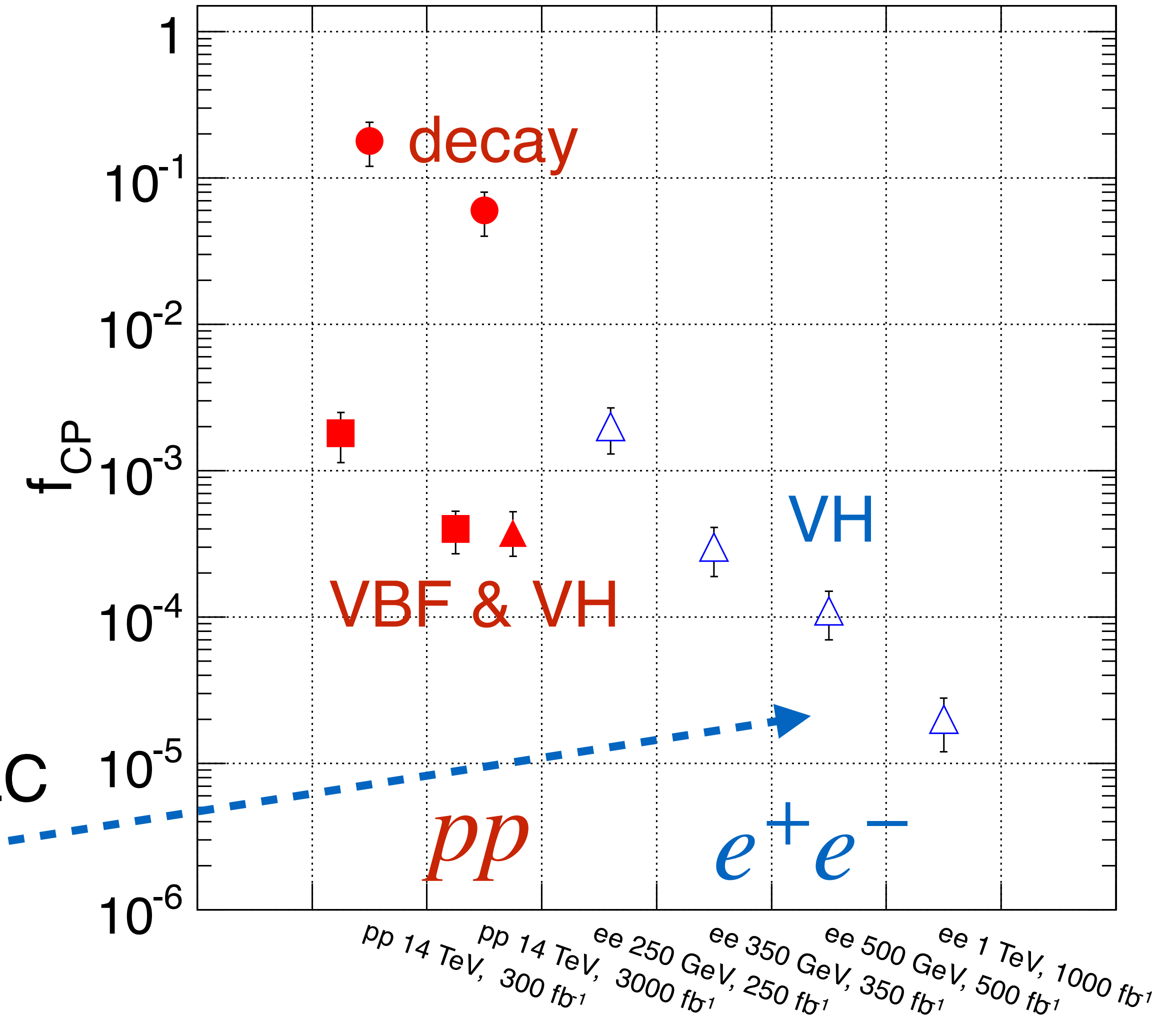


Compare Facilities: e^+e^- and pp

- pp leads to wider spectrum of production modes, more decays
  - — but reach in HVV comparable
  - — $q^2 = s$ at e^+e^-, from PDFs at pp $\Rightarrow$ pros and cons

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-
E (GeV)	14,000	14,000	250	350	500	1,000
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000
$VVH^{\dagger}$	0.07	0.02	✓	✓	✓	✓
$VVH^{\ddagger}$	$4{\cdot}10^{-4}$	$1.2{\cdot}10^{-4}$	$7{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$8{\cdot}10^{-6}$
$VVH^{\diamond}$	$7{\cdot}10^{-4}$	$1.3{\cdot}10^{-4}$	✓	✓	✓	✓
ggH	0.50	0.16	–	–	–	–

arXiv:1310.8361



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— benefit from q^2 sensitivity at LC

— may want to compare with q^2 "roll-off" not clearly defined…

Update to recent LHC projections to HL-LHC

- Higgs Physics at the HL-LHC and HE-LHC

  WG2 report: arXiv:1902.00134

  earlier HVV projections are confirmed:

  with CMS & ATLAS full simulation

Collider	pp	pp
E (GeV)	14,000	14,000
$\mathcal{L}$ (fb^{-1})	300	3,000
$VVH^{\dagger}$	0.07	0.02
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$VV \to H \to 4\ell$ production

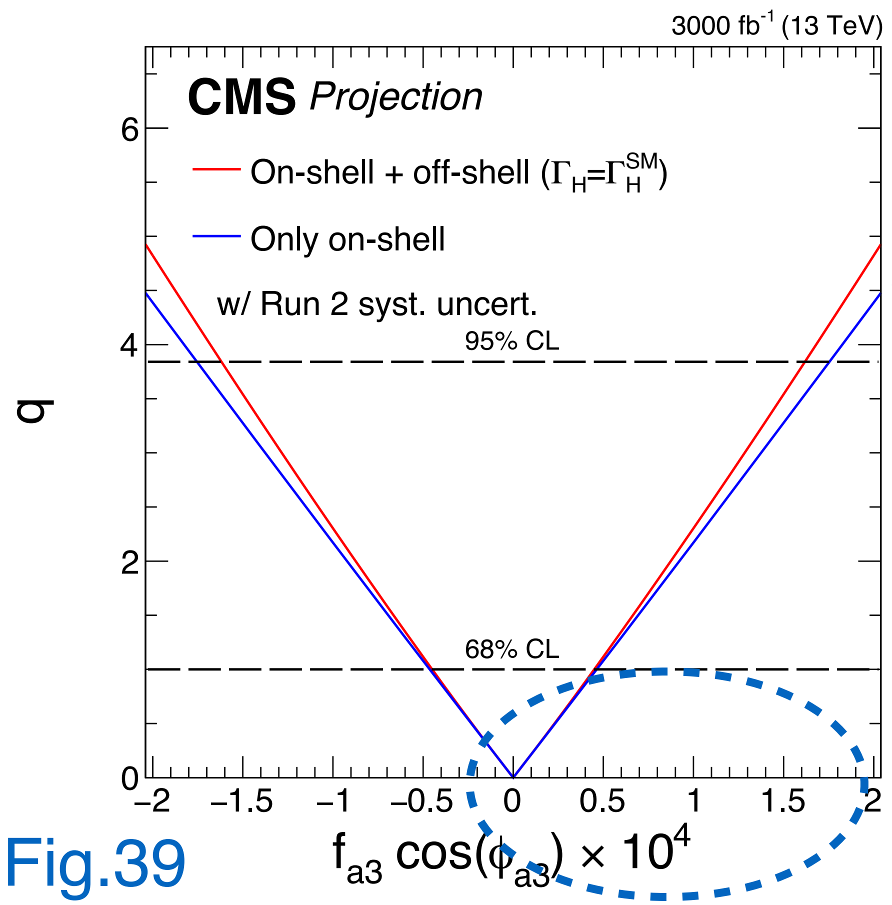


Fig.39

$H \to ZZ \to 4\ell$ decay

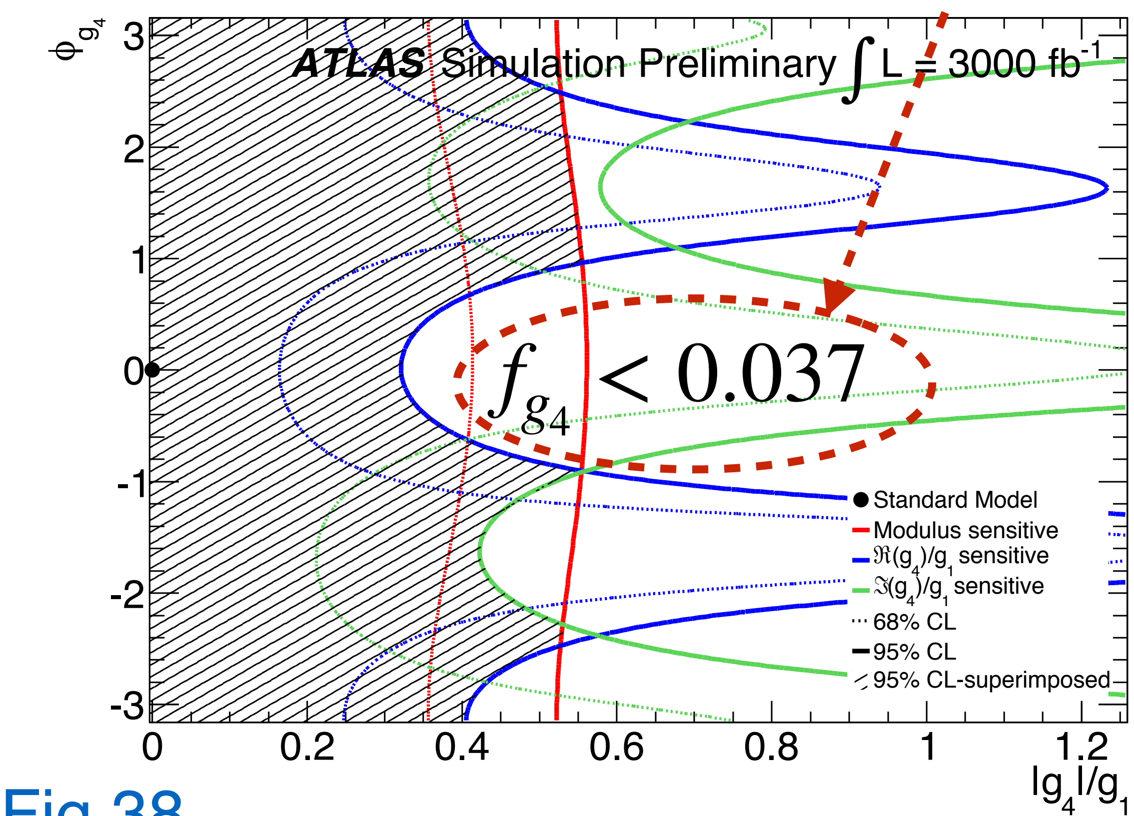


Fig.38

- agreement with most recent pheno HVV and Hgg projections arXiv:2002.09888

Update to recent LHC projections to HL-LHC

- Higgs Physics at the HL-LHC and HE-LHC

  WG2 report: arXiv:1902.00134

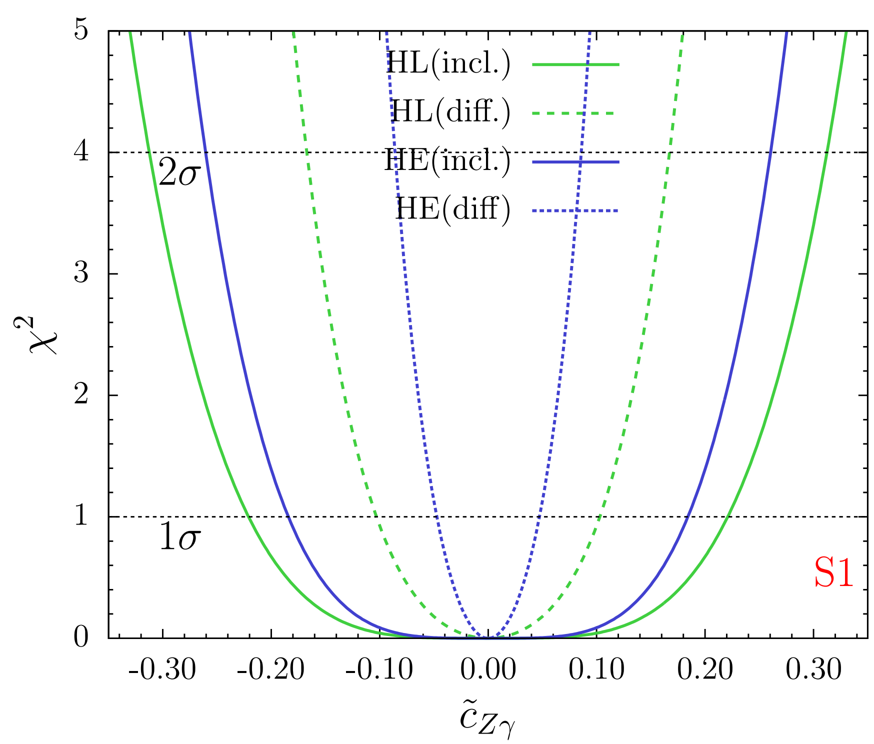
— Global fits also target CP-odd couplings

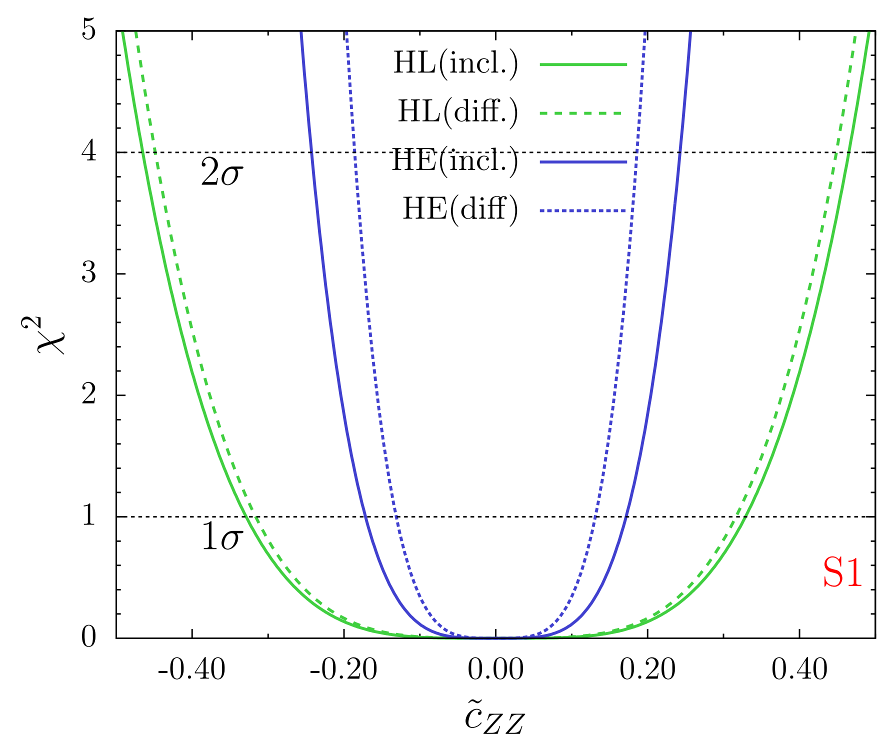
$$\chi^2(\tilde{c}_{Z\gamma}, \tilde{c}_{ZZ}) = \sum_{i,f} \frac{(\mu_{i,f} - \mu_{i,f}^{\text{obs.}})^2}{\Delta_{i,f}^2}$$

— be careful to interpret yield as CP…

CP-even CP-odd

$$\begin{aligned}
\mu_{ZH}^{14\text{TeV}} &= 1.00 + 0.54\,\tilde{c}_{Z\gamma}^2 + 2.80\,\tilde{c}_{ZZ}^2 + 0.95\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ} \\
\mu_{WH}^{14\text{TeV}} &= 1.00 + 0.84\,\tilde{c}_{Z\gamma}^2 + 3.87\,\tilde{c}_{ZZ}^2 + 3.63\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ} \\
\mu_{\text{VBF}}^{14\text{TeV}} &= 1.00 + 0.25\,\tilde{c}_{Z\gamma}^2 + 0.45\,\tilde{c}_{ZZ}^2 + 0.45\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}
\end{aligned}$$



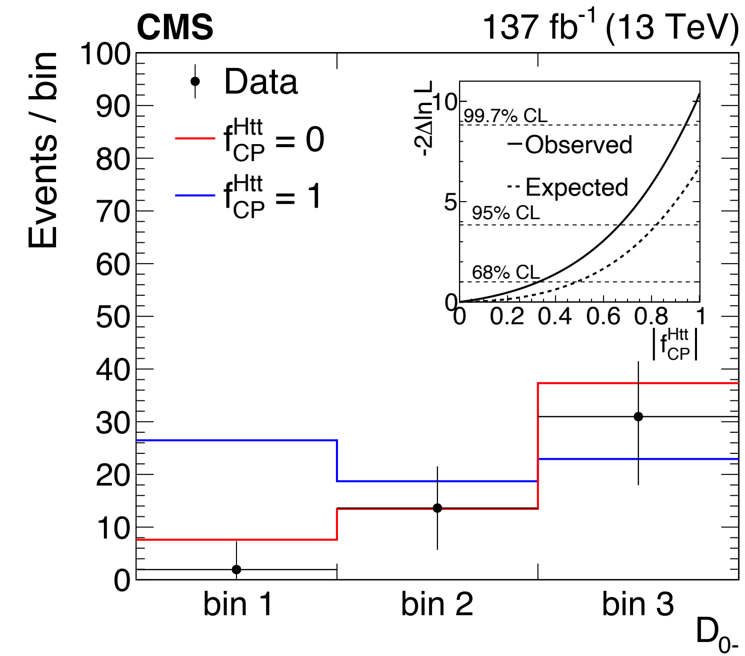


Fermion couplings: $t\bar{t}H$ at pp

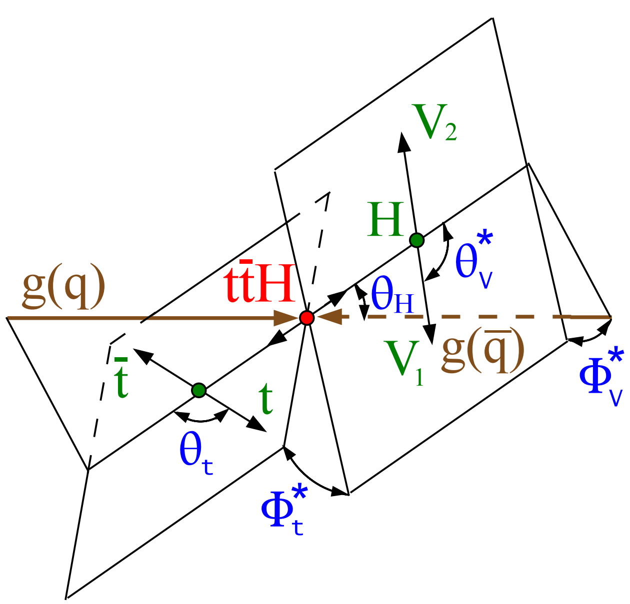
- Very first test of CP in Hff last year:
  - $t\bar{t}H$ spin-off from Snowmass-2013

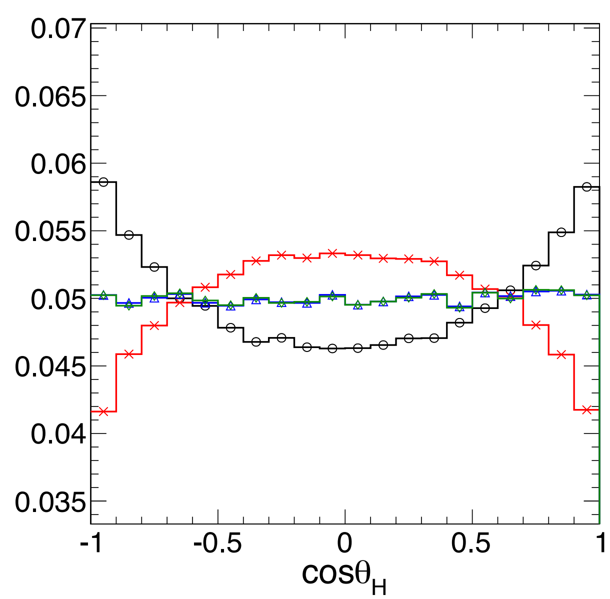
pheno projection agreement with CMS/ATLAS: [arXiv:1606.03107]

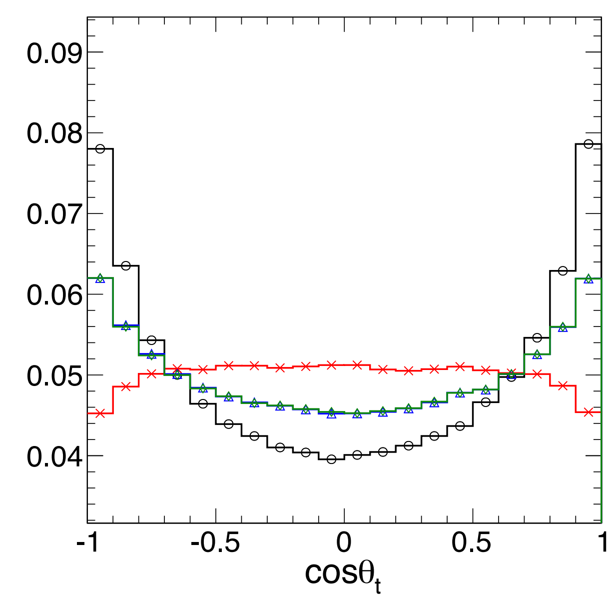
  - reach $f_{CP} \sim 0.1$ $(\alpha \sim 18^\circ)$ at HL-LHC
  - no sensitivity to $2\mathrm{Re}\left(A_{\mathrm{CP\,even}} A^*_{\mathrm{CP\,odd}}\right)$
  - need di-lepton channel for CP interf: [arXiv:1507.07926]
  - similar in tH ; no sensitivity to $b\bar{b}H$, or other light q

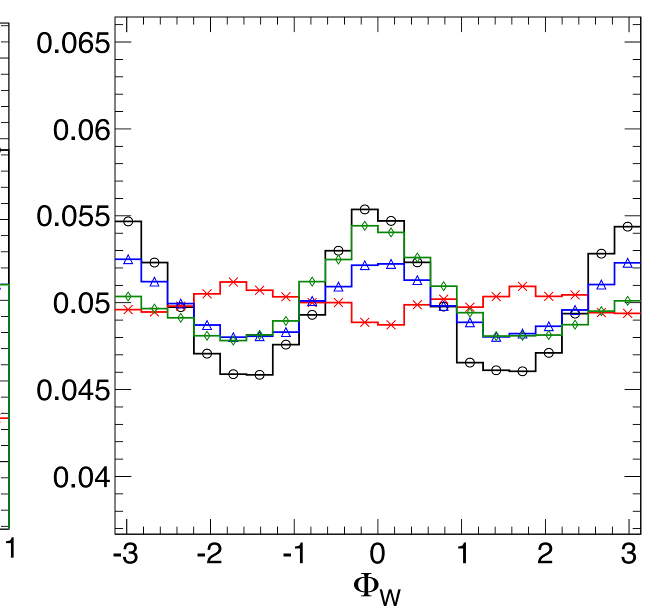


CMS [arXiv:2003.10866]
ATLAS [arXiv:2004.04545]





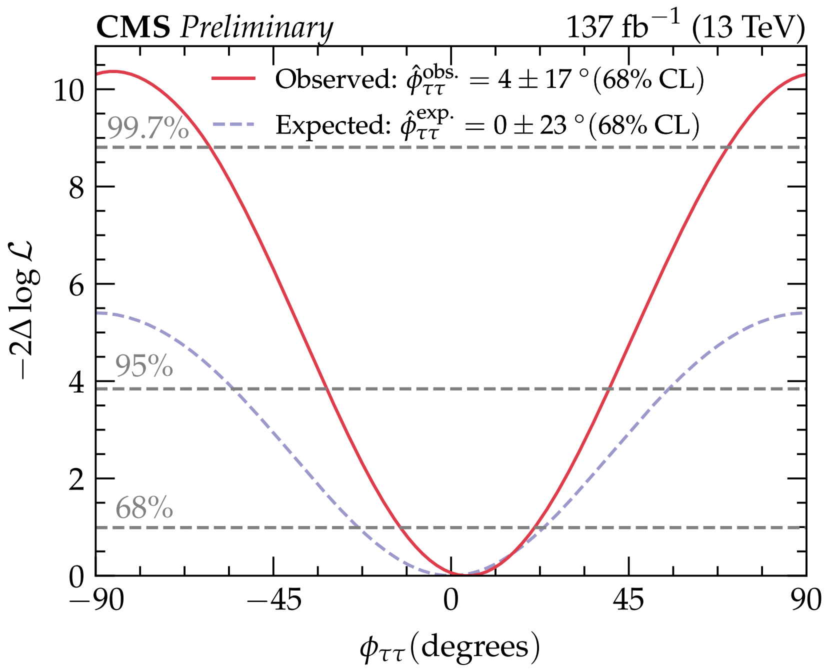


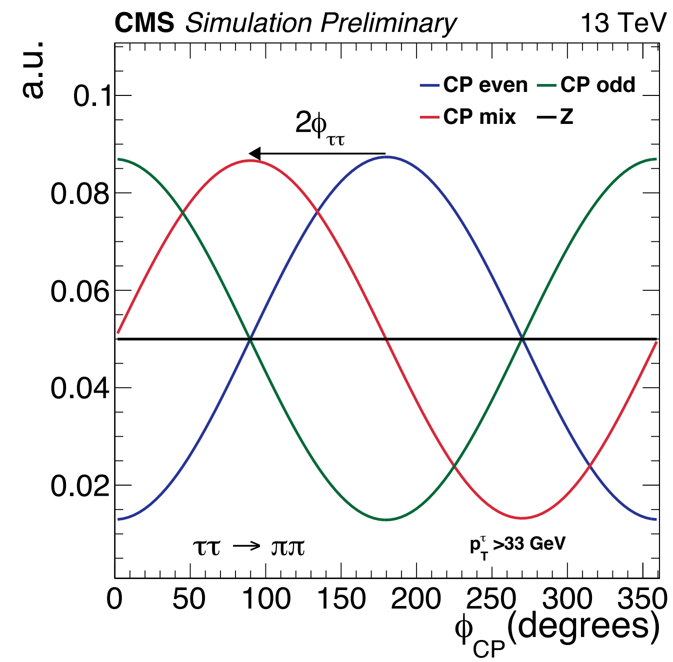


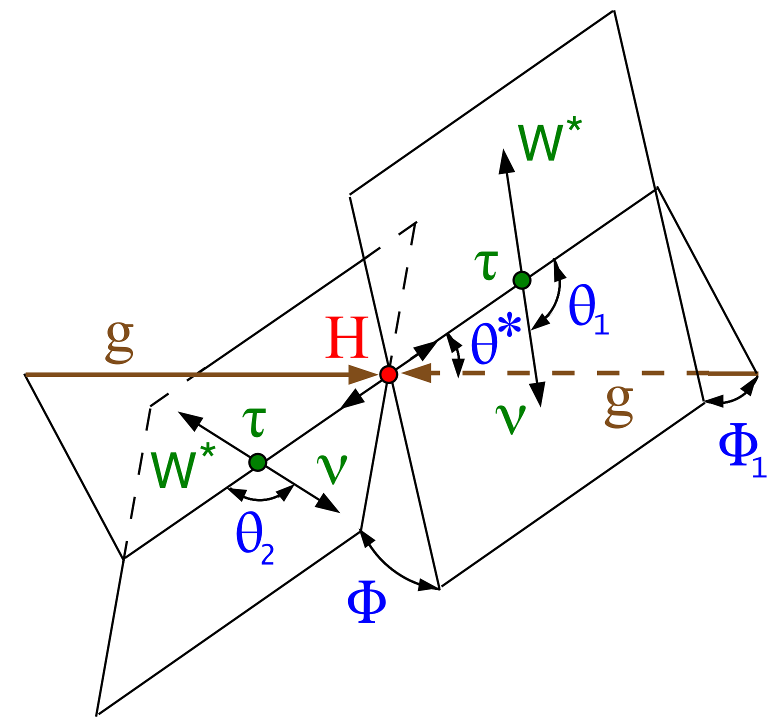
- Make comparison to LC e^+e^-, but looks statistics limited…

Decay: $H \to \tau^+\tau^-$ at pp

- Very first test of CP in $H\tau\tau$ last year: CMS: [CMS-HIG-20-006]







pp pheno studies at Snowmass-2013: [arXiv:1308.1094]

— reach $f_{CP} \sim 0.04$ $(\alpha \sim 11°)$ at HL-LHC

— will benefit from CMS (above) and ATLAS (?) studies, may be $\alpha \sim 5°$?

e^+e^- pheno studies at Snowmass-2013: [arXiv:1308.2674]

— the only CP in Hff at e^+e^- $\sqrt{s} < 500$ GeV

— reach $f_{CP} \sim 0.008$ $\left(\alpha \sim 5°\right)$ at e^+e^- ref. lumi

Summary and Plans

- Higgs CP is a good reference measurement for Snowmass-2022
  - — Snowmass-2013 is already a good starting point
  - — Gitlab area created: https://gitlab.cern.ch/snowmass21-ef01/higgs-cp
- Benefit from the past 8 years + 1 year ahead
  - — sharpen theoretical expectations / models
  - — connect to broader EFT
  - — recent ATLAS & CMS analyses provide good guide for pp
  - — comparison to e^+e^- may be improved
  - — $\gamma\gamma$ & $\mu^+\mu^-$ date back to Snowmass-2001, but may be not a priority…

$$f_{\rm CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\rm CP\,odd}}{\Gamma_{H\to X}^{\rm CP\,odd} + \Gamma_{H\to X}^{\rm CP\,even}}$$

- Focus on CP in:

HWW, HZZ	— dominant tree-level HVV
$HZ\gamma, H\gamma\gamma, Hgg$	— loop HVV with massless V
$Htt, H\tau\tau, H\mu\mu$	— fermion Hff

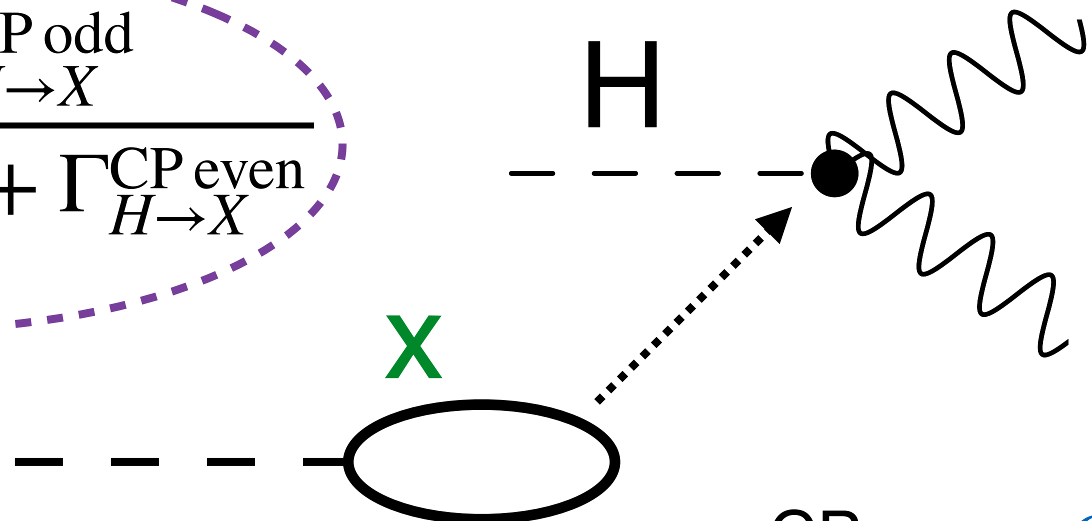
& think about anything else…

BACKUP

Targeted CP-sensitive Couplings

- Look at effective couplings, either within EFT or not

$$f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{\text{CP odd}}}{\Gamma_{H\to X}^{\text{CP odd}} + \Gamma_{H\to X}^{\text{CP even}}}$$

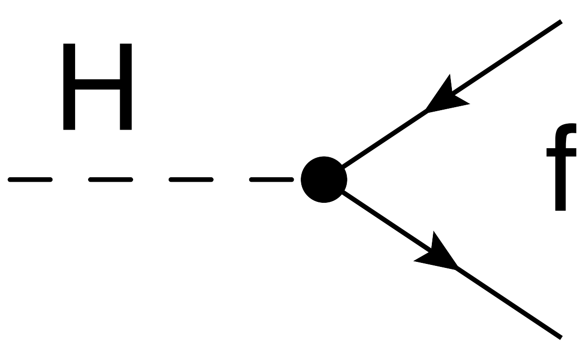


(same for $H \to \gamma\gamma, Z\gamma$)

CP-even a_2^{gg} & CP-odd a_3^{gg} couplings

e.g. fermion loop $a_2^{gg} = -\alpha_s \kappa_Q/(6\pi)$ & $a_3^{gg} = -\alpha_s \tilde{\kappa}_Q/(4\pi)$

- Target HVV, Hgg, Hff couplings



$$A(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\,\tilde{\kappa}_f\gamma_5\right)\psi_f$$

CP-even CP-odd

Targeted CP-sensitive Parameters

- Somewhat more complicated with V=Z,W

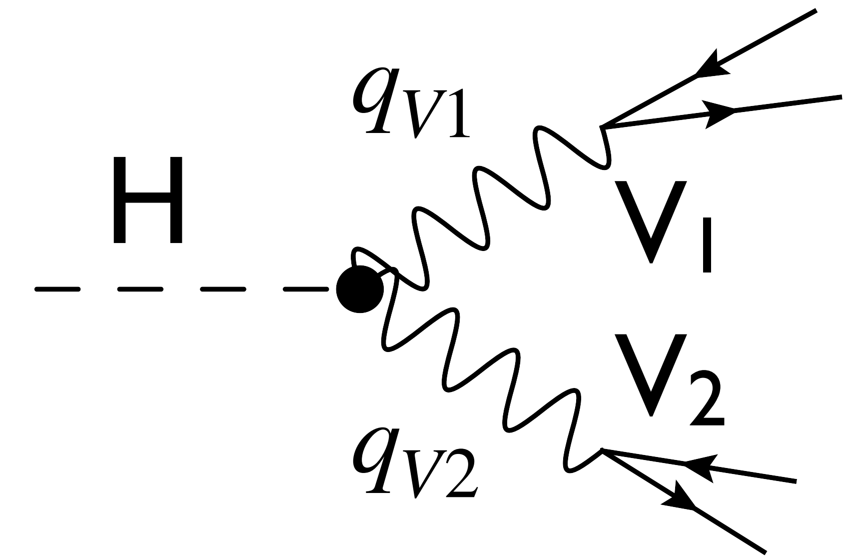
$$A(\mathrm{HVV}) = \frac{1}{v}\left[\boxed{a_1^{\mathrm{VV}}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^*$$

tree-level SM

$$+\frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \boxed{\frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},}$$

CP-even

CP-odd



- May attempt full EFT expansion, but not necessarily the goal in this study…

$$\left|A_{\mathrm{CP\,even}}\right|^2 \quad +2\mathrm{Re}\left(A_{\mathrm{CP\,even}} A_{\mathrm{CP\,odd}}^*\right) \quad + \left|A_{\mathrm{CP\,odd}}\right|^2$$

do not constrain to SM rate

$\int = 0 \quad \Rightarrow$ kinematic distributions

true CP-sensitive observation but not always available

suppressed in EFT

have to be clear if this term dominates

$$f_{CP} = \frac{\left|A_{\mathrm{CP\,odd}}\right|^2}{\left|A_{\mathrm{CP\,even}}\right|^2 + \left|A_{\mathrm{CP\,odd}}\right|^2} = \sin^2(\alpha_{\mathrm{eff}})$$

$$f_{\mathrm{CP}}^{HX} \equiv \frac{\Gamma_{H\to X}^{\mathrm{CP\,odd}}}{\Gamma_{H\to X}^{\mathrm{CP\,odd}} + \Gamma_{H\to X}^{\mathrm{CP\,even}}}$$

parameter of interest